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Light Water Reactor Sustainability Program

Risk-informed multi-physics best-estimate plus uncertainties (BEPU) application development of RELAP5-3D perturbation model

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Risk-Informed Multi-Physics Best-Estimate Plus Uncertainties (BEPU) Application Development of RELAP5-3D Perturbation Model

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EXECUTIVE SUMMARY

The United States nuclear industry is facing a strong challenge to ensure maximum safety while enhancing economic benefit. Safety is a key parameter to all aspects related to light water reactor (LWR) nuclear power plants (NPPs), especially cost savings. Since the goal is to extend the lifetimes of these NPPs, the traditional deterministic safety concept may not guarantee a current economic asset. The Light Water Reactor Sustainability (LWRS) Program has been promoting a wide range of research and development (R&D) in this field to maximize the safety, economics, and performance of these NPPs through improved scientific understanding.

One of the best practices to achieve this goal is to identify and optimize safety margins, which can lead to cost reduction. To do this, under the LWRS framework, the Risk-Informed Systems Analysis (RISA) Pathway will focus on the optimization of safety margin and minimization of uncertainties to ensure both safety and economics at the highest level. The RISA Pathway will provide enhanced capabilities for analyzing and characterizing LWR systems performance by developing and demonstrating methods, tools, and data to enable risk-informed margins management (RIMM).

The goals of the RISA Pathway are twofold: (1) deploy the risk-informed tools and methods that enable better representation of safety margins and factors that contribute to cost and safety; and (2) conduct advanced risk assessment applications with industry to support margin management strategies that enable more cost-effective plant operation. The tools and methods provided by the RISA Pathway will support effective margin management for both active and passive safety systems, structures, and components (SSC) of an NPP.

The tools and methods used in the RISA Pathway should have high confidence and highest technical maturity for and implementation to industry at its current setting. They should also have a capability to support risk-informed decision making for both probabilistic and deterministic elements of safety. The RISA Pathway will, therefore, perform a comprehensive assessment of verification and validation (V&V) status of RISA Toolkit to enhance credibility RISA Toolkit which be used by industry.

This report summarizes RELAP5-3D development activities for best estimated and uncertainty (BEPU) capability to support ongoing RISA Pathway pilot projects for risk-informed uncertainty quantification applications. Work scope includes (1) development of initial perturbation model for selected closure laws and (2) testing of suitable probability distribution functions (PDF) for the selected correlations. Developed BEPU modules are tested with selected separate effect cases and compared with conventional thermal-hydraulics model.

CONTENTS

FIGURES

TABLES

ACRONYMS

ABWR	Advanced Boiling Water Reactor
AOO	Anticipated Operational Occurrence
API	Application Programming Interface
APWR	Advanced Pressurized Power Reactor
ATWS	Anticipated Transients Without Scram
BAF	Bottom of Active Fuel
BEMUSE	Best Estimate Methods Uncertainty and Sensitivity Evaluation
BE	Best Estimate
BEPU	Best Estimate Plus Uncertainty
BWR	Boiling Water Reactor
CANDU	CANada Deuterium-Uranium reactor
CCFL	Counter-Current Flow Limitation
CET	Combined Effect Test
CFR	Code of Federal Regulations
CHF	Critical Heat Flux
CSAU	Code Scaling, Applicability and Uncertainty
CSNI	Committee for the Safety of Nuclear Installations
DBA	Design Basis Accident
DNB	Departure from Nucleate Boiling
DNBR	Departure from Nucleate Boiling Ratio
DOE	Department Of Energy
ECCS	Emergency Core Cooling System
EM	Evaluation Model
EMDAP	Evaluation Model Development and Assessment Process
FA	Fuel Assembly
FLECHT	Full Length Emergency Core Heat Transfer
FOM	Figure of Merit
FSAR	Final Safety Analysis Report
FY	Fiscal Year
HPC	High-Performing Computing
INL	Idaho National Laboratory

ITF	Integral Test Facility
IUQ	Inverse Uncertainty Quantification
LBLOCA	Large Break Loss Of Coolant Accident
LOCA	Loss Of Coolant Accident
LWR	Light Water Reactor
LWRS	Light Water Reactor Sustainability
MSLB	Main Steam Line Break
NEA	Nuclear Energy Agency of the OECD
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
NUREG	Nuclear Regulatory Report
OECD	Organization for the Economic Cooperation and Development
PCT	Peak Clad Temperature
PDF	Probability Density Function
PIRT	Phenomena Identification and Ranking Table
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
RAVEN	Risk Analysis Virtual ENvironment code
R&D	Research and Development
RELAP5-3D	Reactor Excursion and Leak Analysis Program 5 – 3D
RG	Regulatory Guide
RIA	Reactivity Initiated Accident
RI-MP-BEPU	Risk-Informed Multi-physics BEPU
RISA	Risk-Informed System Analysis
RISMC	Risk Informed Safety Margin Characterization
SBLOCA	Small-Break Loss-Of-Coolant Accident
SEASET	Separate Effects And System Effects Tests
SET	Separate Effect Tests
SMR	Small Modular Reactor
TH	Thermal-hydraulic
UAM	Uncertainty Analysis in Best-Estimate Modeling LWRs
UMAE	Uncertainty Method based on Accuracy Extrapolation
UP	Upper Plenum

UQ	Uncertainty Quantification
U.S.	United States

1. INTRODUCTION

1.1 Background

Many of ongoing RISA Pathway pilot projects are using and planning of RELAP5-3D thermal-hydraulics code for risk-informed analysis during postulated scenario of nuclear power plants. The analysis mainly uses risk-informed approach based on probabilistic risk assessment (PRA) and eventually aiming to include uncertainty quantification (UQ), notably, Risk-Informed Multi-Physics Best Estimate Plus Uncertainties (RI-MP-BEPU) analysis. The risk-informed analysis will be covered by RAVEN and SAPHIRE software, which has been used for various PRA applications, however, RELAP5-3D does not support direct uncertainty analysis. In 2019, the RISA Pathway performed technical maturity assessment of RELAP5-3D. The assessment study remarked the lack of the uncertainty analysis capabilities to perform full BEPU analysis in RELAP5-3D and proposed immediate development of certain feature to use in RISA Pathway pilot projects [1].

The BEPU method requires following three applications: uncertainty quantification (UQ) methods, determination of input parameter Probability Density Functions (PDFs), and the propagation of these PDF to RELAP5-3D. This will derive the PDF of the Figure of Merits (FOMs). Current RELAP5-3D allows the possibility to perturb few relevant parameters, but most important parameters for perturbation capabilities (e.g., closure laws) still need to be developed for RI-MP-BEPU application.

The objectives of this development activity are as follows:

- Implement full BEPU analysis capability to RELAP5-3D
- Improve RAVEN to perform risk-informed analysis by using classical/dynamic PRA
- Demonstrate and benchmark RI-BEPU capability through selected Anticipated Operation Occurrence (AOO) and DBA scenarios
- Develop and validate Multi-Physics BEPU model
- Support existing and future industry pilot projects, which plan to employ the RI-MP-BEPU model.

Development activity will include following three phases:

Phase 1 - Modification of RELAP5-3D of selected closure laws and correlations for direct perturbation.

- Develop technical basis of RELAP5-3D perturbation models.
- Apply PDFs to selected closure laws.
- RELAP5-3D modification for developed perturbation models and demonstration.

Phase 2 – Coupling of RELAP5-3D and RAVEN to extend RELAP5-3D for risk-informed BEPU

- Improve RAVEN for direct access to RELAP5-3D output binary files.
- Develop extension of RAVEN to manage RELAP5-3D control logic.

Phase 3 – Verification and validation of risk-informed BEPU model with various AOO and DBA scenarios

- Improvement of model for future risk-informed multi-physics BEPU application

Phase 1 and 2 could be performed together since RELAP5-3D and RAVEN codes have separate development team and work area. Phase 3 activities can be started from Phase 1 and 2 to verification and validation (V&V) as model development and code upgrade progresses.

The developed capability will be validated through Organization for Economic Co-operation and Development/Nuclear Energy Agency's activity on "Benchmark for Uncertainty Analysis in Best-Estimate Modeling," which aims to perform comprehensive benchmark study of various nuclear systems to implement uncertainty analysis method.

1.2 RELAP5-3D: Overview

RELAP5-3D (Reactor Excursion and Leak Analysis Program) is computer simulation software dedicated to the nuclear power plant operational transient and accident thermal-hydraulics analysis. Developed at Idaho National Laboratory (INL) and originally funded by U.S. Atomic Energy Commission (current U.S. NRC), the RELAP5-3D is the state-of-the art for reactor safety analysis, reactor design, simulator training of operators, and nuclear industrial facility licensing.

First version of RELAP5 was developed in 1979 as RELAP5/MOD0. Main improvement from previous RELAP series is change from one-fluid to two-fluid model with a different set of governing equations for the liquid and gas phases as well as significant improvement on capability of small-break LOCA analysis. Another important update was change to FORTRAN 77. This RELAP5 has been updated until RELAP5/MOD3.2.

By support from U.S. Department of Energy (DOE), RELAP5-3D was developed in mid-1990's by INL. In the late 1990s, the International RELAP5 Users Group (IRUG) was organized to support international RELAP5-3D users and to disseminate code worldwide. Notable features of the RELAP5-3D are full three-dimensional hydrodynamics with rectangular, cylindrical and spherical geometries and introduce of the RELAP5-3D Graphical User Interface (RGUI). RELAP5/Ver. 2.0 was the first expansion to the Windows operating system. RELAP5-3D/Ver. 2.4 was the final FORTRAN 77 code version. Latter versions are built with Fortran 90/95/2003. RELAP5-3D/Ver. 3.0 was the beta-test release of the first fully Fortran 95 version. As of 2019, RELAP5-3D/Ver. 4.4.2 is the most recent release and the most robust, verified, and validated product of the RELAP5 series.

Main purpose of the RELAP5-3D code is for best-estimate transient simulation of light water reactor coolant systems during postulated accidents. The code models the coupled behavior of the reactor coolant system and the core for loss-of-coolant accidents and operational transients such as anticipated transient without scram, loss of offsite power, loss of feedwater, and loss of flow. A generic modeling approach is used that permits simulating a variety of thermal hydraulic systems. Control system and secondary system components are included to permit modeling of plant controls, turbines, condensers, and secondary feedwater systems. RELAP5-3D also has three-dimensional thermal hydraulics and neutron kinetic modeling capabilities. The multi-dimensional component in RELAP5-3D was developed to allow the user to accurately model the multi-dimensional flow behavior that can be exhibited in any component or region of a nuclear reactor coolant system. There is also two-dimensional conductive and radiation heat transfer capability and modeling of plant trips and control systems. The features of the RELAP5-3D are very well stated at user manual Volume 1.

RELAP5-3D allows for the simulation of the full range of reactor transients and postulated accidents, including:

- Trips and controls
- Component models (pumps, valves, separators, branches, etc.)
- Operational transients
- Startup and shutdown
- Maneuvers (e.g. change in power level, starting/tripping pump)
- Small and large break Loss Of Coolant Accidents (LOCA)
- Anticipated Transient Without Scram (ATWS)
- Loss of offsite power
- Loss of feedwater
- Loss of flow
- Light Water Reactors (PWR, BWR, APWR, ABWR, etc.)
- Heavy Water Reactors (e.g. CANDU reactor)
- Other types of the reactor (e.g. SMR, GenIV, etc)

2. NEEDS FOR RELAP5-3D BEST ESTIMATE PLUS UNCERTAINTY

This section presents a summary of the available thermal-hydraulic safety analyses methods to perform Best-Estimate Plus Uncertainty (BEPU) analysis for a risk-informed safety analysis application. In particular, the section presents the needs to introduce code models' uncertainties propagation for the RELAP5-3D code in order to allow supporting RISA Pathway pilot projects.

2.1 Introduction

2.1.1 Towards BEPU methods

The use of the so-called BEPU methods in the United States, originates in the research performed by the U.S. NRC in the 1970s and 1980s for reducing the level of conservatisms, i.e. for increasing the knowledge of the different phenomena occurring during an operational transient or an accident. In particular, these efforts led to a revised set of rules of the 10CFR50.46 for the evaluation of the Emergency Core Cooling Systems (ECCS) performances [2] and to the issuing of the Regulatory Guide 1.157 [3] on using Best-Estimate (BE) methods, provided the uncertainty of the figure of merits (FOM) are quantified.

A Technical Program Group of the NRC also introduced in those years a methodology for performing BEPU analyses for LBLOCA named CSAU (Code Scaling, Applicability and Uncertainty, [4]. Since then, several research institutions developed new BEPU methods and several workshops [5], [6], and specific conferences [7] has been held for discussing the progresses in the field.

2.1.2 The Evaluation Model

Performing safety analyses implies the development of a computational framework or an Evaluation Model (EM), which may include:

- special analytical models;
- input decks;
- one or more computer codes;
- all the information that allow the specific application (e.g., experimental data, reports, etc.).

The U.S. NRC has developed a dedicated guideline, the regulatory guide 1.203 [8] to help the developing and the assessment of an EM (EMDAP). The EMDAP principles are based on the aforementioned CSAU method. EMDAP is a multi-step process that allows the user to assess the adequacy of the EM to simulate the scenario of interest and to predict the requested safety parameters. The 20-steps point of an EMDAP are showed in the scheme of Figure 2-1.

The four main elements of EMDAP are: 1) establish the requirements of the EM, 2) develop the assessment base for supporting the requirements, 3) develop the EM, finally 4) assess the adequacy of the EM.

A key step of EMDAP, relevant for the activities described in this report, is the Step 4 of Element 1: identification and ranking of phenomena and process as they affect the FOMs. The Step 4 is the so-called Phenomena Identification and Ranking Table, or PIRT (introduced with the CSAU method). The transient scenario under analysis has to be divided in distinct phase based on the events taking place. For each phase, the phenomena relevant for the FOM have to be identified and ranked. As it will be showed in section 3, the PIRT is very important for the uncertainty analysis.

Element 4 of EMDAP concerns the assessment of evaluation model adequacy and the uncertainty evaluation. Element 4 is divided in two parts, with the first (steps 13-15) concerning a bottom-up evaluation of the closure relations of the code, including applicability, fidelity and/or accuracy and scalability. Those are very important steps that involve the use of Separate Effect Test (SET) data and that helps in the quantification of the closure laws uncertainties.

The second part (steps 16-19) concerns a top-down evaluation of the codes governing-equations, numeric, and the integrated performances of the EM.

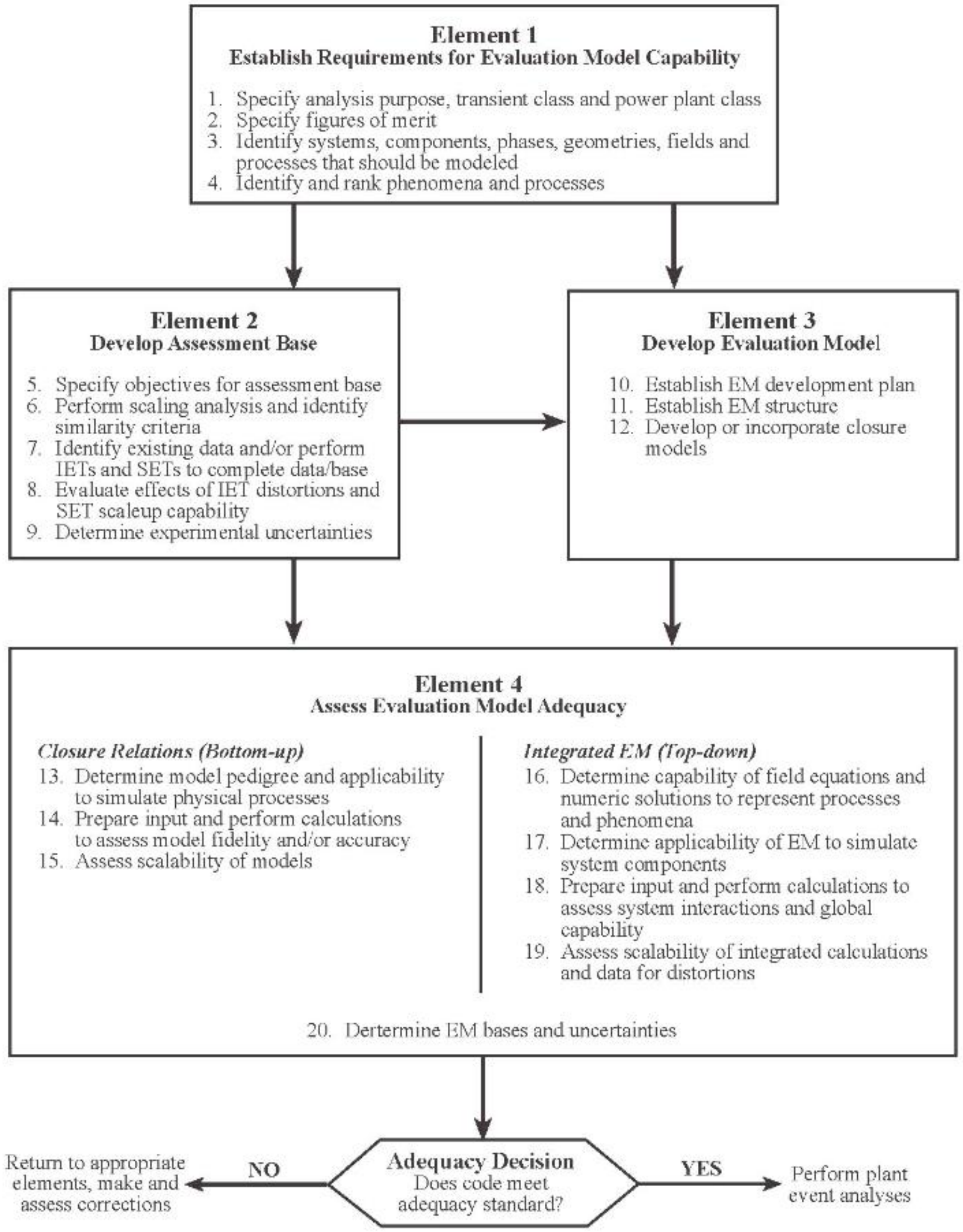

Figure 2-1. Elements of EMDAP [8].

In the following section, we will summarize how different EMs are used for obtained conservative or more realistic safety analyses.

2.1.3 Safety Analysis Options

According to the IAEA, there are four different possible approaches available for a safety analysis, as it is shown in Table 2-1.

Table 2-1. Options for combination of a computer code and input data [9].

Option	Computer Code	Availability of Systems	Initial and Boundary Conditions
Conservative	Conservative	Conservative Assumptions	Conservative input data
Combined	Best Estimate	Conservative Assumptions	Conservative input data
Best Estimate	Best Estimate	Conservative Assumptions	Realistic plus uncertainty; partly most unfavorable conditions
Risk Informed	Best Estimate	Derived from PSA	Realistic input data with uncertainties

The conservative approach (first option) has historically been the first approach adopted in the U.S., and it was codified in 1974 in the aforementioned 10CFR50.46 [10] and in its Appendix K [11]. At that time, the conservative approach was justified by the lack of knowledge of the physical phenomena occurring during accidental phases, and it was engineered in order to maximize the analysis consequences while using restrictive acceptance criteria.

The second option (BE code + conservative assumptions and input data) is still being used in many Countries although it is not allowed in the US by the 10CFR50.46 rule. The use of conservative assumptions and input data has to guarantee that the all uncertainties are being properly bounded. Validation of the BE code, sensitivities studies and proper use of conservative data has to be demonstrated and documented.

The third option (BEPU analysis) allows the use of BE code and of realistic initial and boundary conditions. Uncertainties of the code and of the boundary and initial conditions have to be identified, quantified and combined. An adequate number of sensitivities analyses should also be produced, identifying also possible code ‘cliff edge effects. Generally, a mixture of option 2 and 3 analyses was performed, depending on the availability of realistic input data. In the years following the 1989 regulatory updates, the introduction of: advanced experimental programs, BE computer codes (RELAP5, TRAC, CATHARE, etc.) and then of new BEPU methods, e.g. [12], [13], [14], has led to a better understanding of the physical phenomena, to an increase of the safety margins and to an enhancement of the economy of the nuclear power plants (see Figure 2-2).

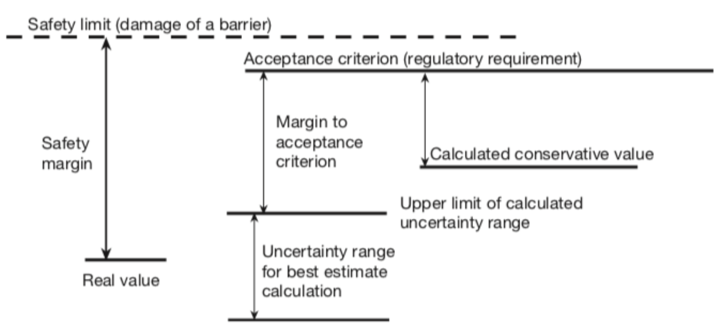

Figure 2-2. Safety margins with conservative and BEPU calculations [15].

After initial applications to mostly LB-LOCA scenarios, BEPU methods has been also extended to other types of accidents like SB-LOCA, e.g. [16], and non-LOCA, e.g. [17], [18], [19]. Several BEPU methods are today available to the nuclear industry, e.g. [20], [21], [22] and they have become the standard approach for the nuclear safety analysis.

Option 4 of Table 2-1, is not yet widely used and it is a field of research, but it can be considered as the true BE estimate method. It includes a realistic analysis (i.e. BEPU analysis) combined with probabilistic safety analysis to quantify the availability of safety-significant systems.

Option 4 does not rely, as option 1 and 3, on the use of surrogate-based decision rules (a predefined set of bounding scenarios, or DBAs) but it instead provides a safety analysis based on the real frequency of every possible accidental event and it allows the development of risk-informed decision making [23]. US DOE LWRS Project, RISA pathway, deals with developing methods and performing advanced analysis using option 4. In the next section we will show the necessary steps for performing a BEPU analysis, also using a risk-informed approach.

2.2 Uncertainty Quantification for BEPU

2.2.1 Methodologies for system TH codes

An uncertainty analysis is based on the "…identification and characterization of relevant input parameters (input uncertainty) as well as of the methodology to quantify the global influence of the combination of these uncertainties on selected output parameters (output uncertainty)" [15]. Existing uncertainty analyses methods that are combined with a BE code, can be grouped in two different families [24]:

- Input-driven methods;
- Output-driven methods.

The "input-driven" methods are based on information limited to the inputs: the relevant input uncertainties are identified, and the corresponding input parameters are perturbed according to a proper probability distribution function (PDF) or range.

Thus, the input uncertainties are propagated through the TH code. The result is a distribution/range of the code figure-of-merits (FOMs). Input-driven methods are very popular and are currently used in, e.g. the NRC CSAU method, the GRS method, the Westinghouse ASTRUM method, the Framatome method. A sketch of the input-driven method is given in Figure 2-3.

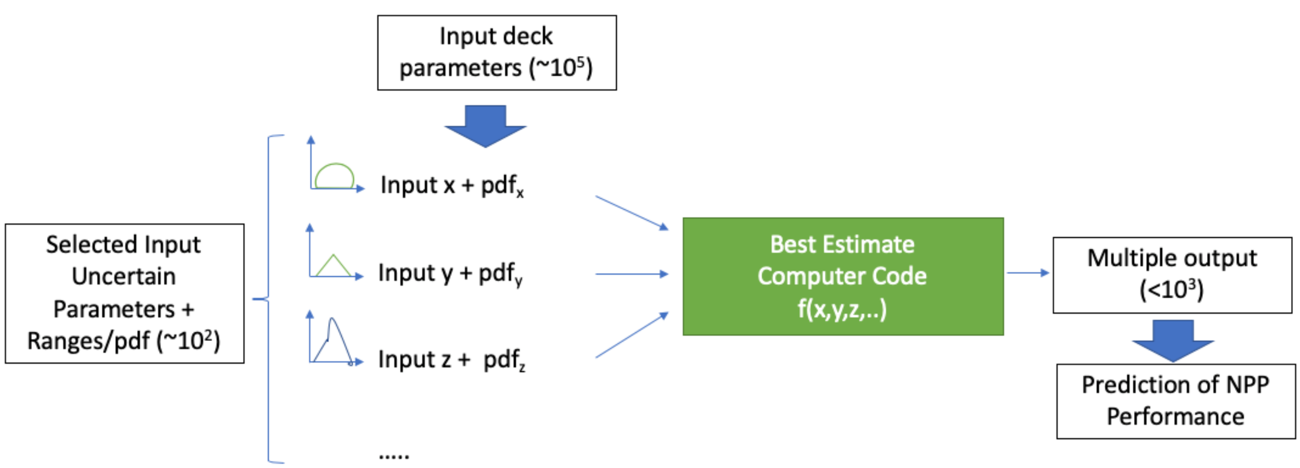

Figure 2-3. Input uncertainties propagation [15].

The "output-driven" methods are instead based on information limited to the code outputs (see Figure 2-4). The code output uncertainty is directly obtained from the available experimental database by extrapolating the accuracy evaluated from relevant experiments performed on integral test facilities (ITF) to the full scale NPP. An example of the output-driven uncertainty method is the UMAE method from University of Pisa, Italy [25].

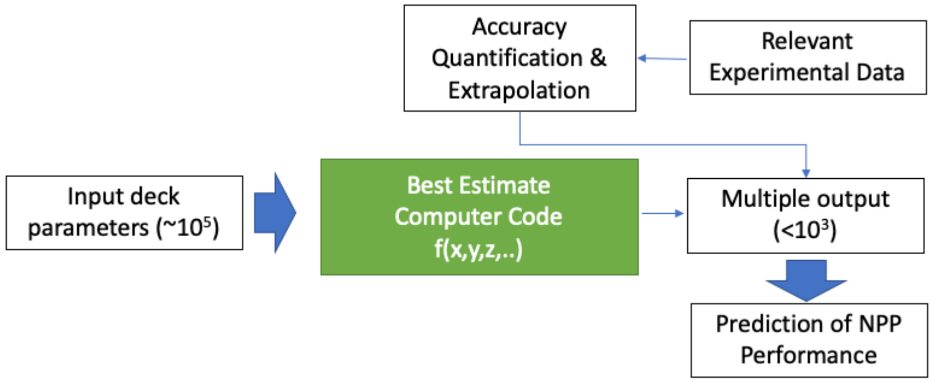

Figure 2-4. Output uncertainties propagation [15].

As stated before, the "input-driven" methods are the most diffused, and they can be further distinguished between probabilistic methods (i.e., methods that identify and assign a PDF to the uncertainties) and deterministic methods (i.e., methods that assign a specific determined range or a bounding value to each input parameter uncertainty). Common to both methods are:

- the identification of code, NPP and transient;
- the identification of the main input uncertainties (see next section).

There are then different ways of propagating the input uncertainties through the code, including Monte Carlo (brute-force, Latin-Hypercube, importance-based sampling), response-surface methods (e.g. in the CSAU), sensitivity-based methods.

The increase in complexity of systems and models in the recent years have limited the application of response surface methods (the number of required calculations increase geometrically with the number of the selected input uncertainties).

On the other hand, the order-statistics methods have become very popular among US institutions and industries since they do not require the number of minimum calculations to the number of input parameters (e.g., Westinghouse ASTRUM method [20], AREVA/Framatome [21] and GE-H methods [26] are based on order-statistics method).

2.2.2 Order-statistics methods

We provide here a short description of the order-statics method, since it will be then used in Chapter 4 for performing the tests for the uncertainty propagations for RELAP5-3D. As it has been described in the previous section, there is a growing consensus toward the use of order statistics methods since it avoid the need of performing thousands of code' runs. Order-statistics, as the name suggest, organizes the samples from the first (the minimum value) to the last (the maximum value). It is a method that implies no assumptions on the FOM PDF and an unlimited number of model uncertainties can be considered at the same time during the sampling process. As reported in [27], order statistics are based on the use of Wilks` formula [28] – which determine the minimum number of calculations:

$$\beta = 1 - \sum_{i=N-m+1}^{N} \frac{N!}{(N-i)!\,i!} \gamma^i (1-\gamma)^{N-i}$$

where γ is the percentile of the bounding value of the FOM, β is the confidence value, N is the number of calculation runs, *m* is the number of outputs in the γ^{th} quartile. As it can be seen in Table 2-2, the number of code runs depends only by the percentage of the bounding value and on the desired confidence level. For example, for satisfying US NRC requirement in 10CFR50.46 that there must be a high level of probability that the regulatory limits are not being exceeded, it is generally assumed that the determined code outputs bound 95% of the population (γ) with 95% confidence (β). Consequently, for m = 1, the minimum number of calculations required are 59.

Table 2-2. Minimum runs using the Wilks formula for m=1 [28].

β/γ	**0.90**	**0.95**	**0.99**
0.90	22	45	230
0.95	29	59	299
0.99	44	90	459

Possible reduction of the conservatisms and of the FOM variability, can be obtained by increasing the number of minimum calculations (N) and by increasing the number of outputs in the γ^{th} quartile (*m*). The results for a 95% percentile / 95% confidence for $m \geq 1$ are given in Table 2-3.

Table 2-3. Minimum runs required, 95% percentile / 95% confidence and *m* ≥ 1.

m	**N**
1	59
2	93
3	124
4	153
10	311
20	548
100	2325

2.2.3 Quantification of Input Uncertainties

International OECD/NEA benchmarks like UAM [29] and BEMUSE [30] have shown a certain maturity of the BEPU methods, however they also highlighted the need of a better understanding and quantification of the input uncertainties, which is a mandatory step in the UQ process and it is often subjected to engineering judgment (see Section 2.1.2). Among the various input uncertainties, the following distinction can be made:

- boundary and initial conditions uncertainties;
- code or physical models uncertainties;
- user effects;
- scaling uncertainties;
- bias uncertainties (unknown unknowns).

While the definition of the boundary and initial conditions uncertainties is generally a matter of obtaining better information from the experimental facilities or the NPP, the identification and quantification of the physical models' uncertainties presents significant more challenges. The derivation of their PDF involves engineering judgment, an assessment of the employed numerical methods and of the experimental data. As matter of fact, models uncertainties often represent the most important uncertainties in the UQ process [30].

Quantifying the models input uncertainties for thermal-hydraulic code, including closure laws is a so-called inverse uncertainty quantification (IUQ) problem and it is today a field of research. Several institutions are exploring different approaches for solving IUQ problem minimizing the engineering judgment, e.g. see [31], [32].

The OECD/NEA has also recently organized a benchmark for the testing the available methods for the quantification of the input uncertainties during the LB-LOCA reflood phase [33]. The main outcomes of this activity were that a more systematic approach is needed for the quantification of closure laws uncertainties. In particular it has been recommended the choice of an adequate quantification database, the qualification of the facilities models, avoiding calibration, the development of a suitable IUQ method and the minimization of user effects [34].

2.3 BEPU activities for LWRS/RISA pathway

2.3.1 Needs

Implementing Option 4 of Table 2-1 (Risk-Informed safety analysis) require the combination of BEPU and probabilistic safety analysis. In order to have a full BEPU analysis, INL thermal-hydraulic system code RELAP5-3D has to have capability of deriving the main models uncertainties. The first step in adding this capability is allow the code user to perturb dedicated input parameters of the most important closure laws invoked by the code during the simulation of an accident. Perturbation of closure laws is today not possible for a user that does not have the possibility to access the source code, therefore the actions described in the next paragraph were taken.

2.3.2 Advancement of the BEPU capabilities for LWRS/RISA pathway

In order to advance INL capabilities in having a BEPU method for the LWRS/RISA pathway, the following actions have been taken the FY2020. In particular:

1. a review of the recent activities in the input uncertainties quantification;
2. identification of the RELAP5-3D source code routines, focusing on those involved in the simulation of the reflood phase;
3. modification of the RELAP5-3D source code, with introduction of new cards options and new source code debugging;
4. testing of the modified RELAP5-3D source code using the FLECHT-SEASET experiments, and perturbing the closure laws input parameters using the RELAP5-3D/RAVEN coupled codes;
5. identifications of the future works.

In the following report sections, points 2 to 5 are documented. In particular: in Section 3, the identification and the description of the RELAP5-3D source code routines for the reflood phase are reported, as well as the description of the source code routines modifications. Section 4 describe the testing of the modified RELAP5-3D source code using the FLECHT-SEASET experiments, coupling the RELAP5-3D/RAVEN codes for performing an UQ test on the PCT. Section 5 presents the conclusions and the future works

3. RELAP5-3D MODIFICATION FOR THE REFLOOD INPUT UNCERTAINTIES

This section presents the modification to the RELAP5-3D source code and input deck for addressing the perturbation of the relevant models' parameters for the LBLOCA transient, focusing on the reflood phase. After a brief introduction on the physics and phenomena involved in the LBLOCA and in the reflood phase, the RELAP5-3D models and routines are described, and the modifications are explained. A final table in the last paragraph summarize the new code input options for performing the perturbation analysis of the selected closure laws for the reflood phase.

3.1 PWR LBLOCA Phenomena

LB LOCAs in LWR can be described through three different phases: blowdown, refill, reflood (see Figure 3-1). Long-term cooling conditions has then to be guaranteed after these three phases.

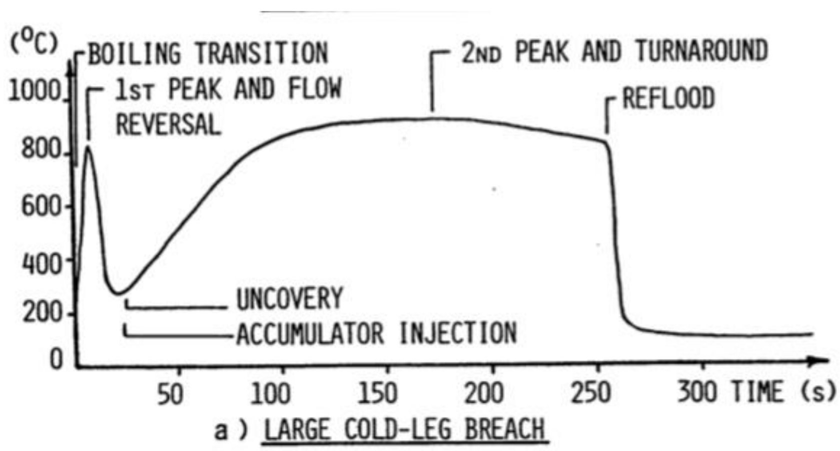

Figure 3-1. LB-LOCA phases in a PWR [35].

In particular, for a PWR we have:

- **Blowdown**: initial phase, occurring after the initial break and lasting generally ~ 30 seconds. The system pressure suddenly decreasing, causing primary coolant flashing and two-phase flow at the break. This phase is ending when the ECCS starts to inject.
- **Refill**: second phase, lasting ~ 10 seconds. ECCS water starts to refill the reactor pressure vessel and the level in the lower plenum start to rise; the phase is ending when the lower plenum is full.
- **Reflood**: third and last phase, lasting ~ 250 seconds. This phase starts when the core liquid level in the lower plenum reaches the bottom of active fuel (BAF). This core reflooding from below allows a cool-down (quenching) of the overheated fuel rods. In some PWR, combined water injection from top and bottom is also possible. During reflood, the coolant channels are experiencing post-CHF heat transfers, and the hot surfaces are cooled down as the liquid front move upward. Quenching/rewetting occurs when the liquid is in permanent contact with the fuel rod surface. As a consequence, the heat transfer fuel rod-coolant, dramatically increase and the clad temperatures have a sharp decrease (see Figure 3-2). The physics of quenching is quite complex and it is strongly depending on the clad temperature. In particular, if the clad temperature is above the minimum stable film boiling temperature, cooling will happen through film boiling. However, if clad axial condition and precursor cooling reduce the clad temperature enough, transition and subcooled boiling will happen.

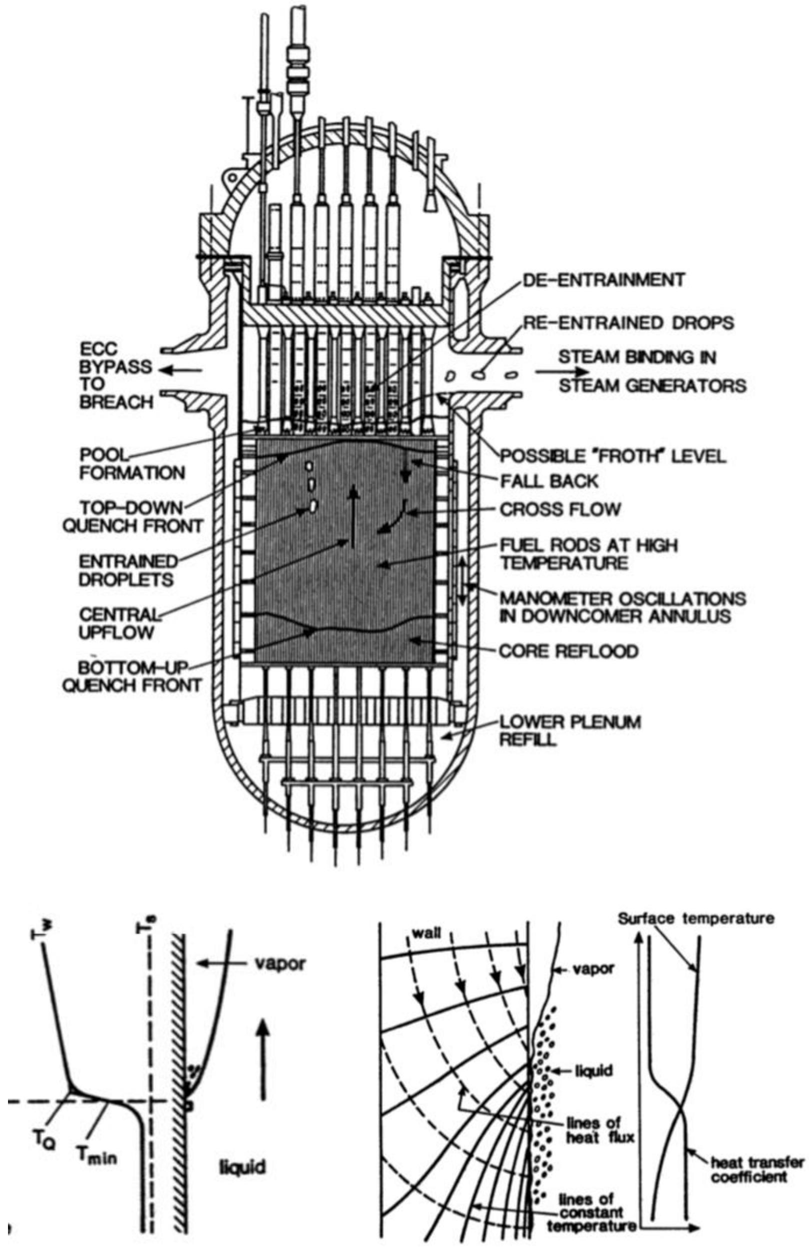

Figure 3-2. Reflood Phase Phenomena [35].

Above the subcooled boiling region, the clad is experiencing film boiling with inverted annular flow regime and dispersed droplet regime (see last sketch of Figure 3-2). The quenching front is then moving upward thanks to the cooldown provided by the liquid droplets, the steam and the axial conduction.

As it can be guessed from Figure 3-1, experiments results and numerical analysis have shown that reflood is one of the most important phases during a LB LOCA, having a relevant effect on the prediction of the final PCT and of the safety margin. This has led during the years to the execution of many bundle test for investigating such a complex phase [36]. They are reported in the following table.

Table 3-1. Phenomena occurring during the Reflood phase [37].

Phenomena	**Occurring** (+: occurring, 0: partially occurring)
Break Flow	+
Phase Separation (condition or transition)	+
Mixing and condensation during injection	+
Core wide void + flow distribution	+
ECC bypass and penetration	0
CCFL (UCSP)	+
Steam binding (liquid carry over, ect.)	+
Pool formation in upper plenum (UP)	+
Core heat transfer incl. DNB, dryout, return to nucleate boiling	+
Quench front propagation	+
Entrainment (Core, UP)	+
De-entrainment (Core, UP)	+
1- and 2-phase pump behavior	0
Non-condensable gas effects	0

The complexity of the reflood phase shown in the previous table, demonstrates that an input uncertainty quantification using only Separate Effect Test (SET) facilities data is not possible. Therefore, the use of Combined Effect Test (CET) and Integral Test (IT) facilities is instead needed.

3.2 Identification of the RELAP5-3D routines

3.2.1 Code architecture

RELAP5-3D is the INL reference BE system thermal-hydraulic code [38]. The code is based on non-homogeneous and non-equilibrium model for the two-phase system. The most prominent attribute that distinguishes the RELAP5-3D code from the previous versions of the RELAP family, is the fully integrated, multi-dimensional thermal-hydraulic and kinetic modeling capability. This removes any restrictions on the applicability of the code to the full range of postulated reactor accidents. The code solves the two-phase system using a semi-implicit or a nearly-implicit numerical scheme.

The source code is organized according to the following scheme [38].

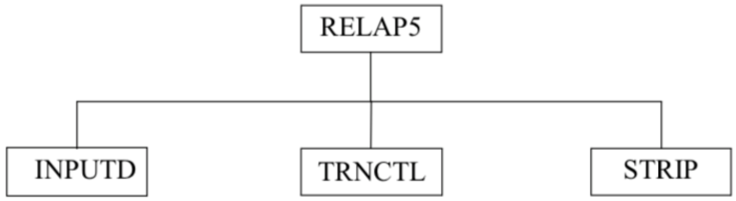

Figure 3-3. RELAP5-3D to level structure [35].

It consists of input block (INPUTD) that processes input, checks input data and prepares required data block for all program options. The transient/steady-steady state block (TRNCTL) handles both steady-state and transient options; the strip (STRIP) block control the output data processing. Going more into details, the transient calculations are organized according to the modular structure reported in Figure 3-4.

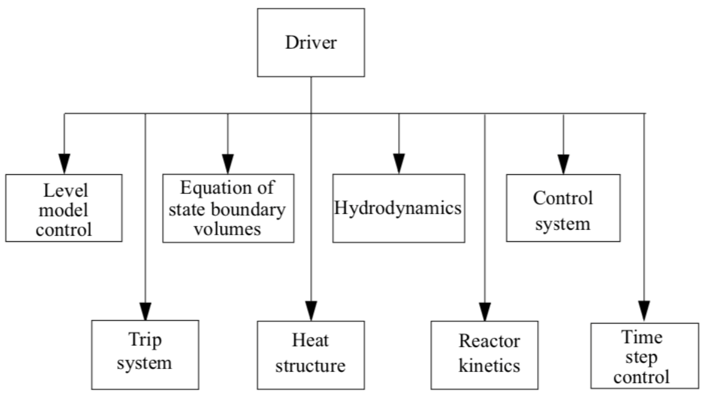

Figure 3-4. RELAP5-3D modular structures for transient calculations.

The relevant routines for the reflood analysis are being called by the hydrodynamics (HYDRO) and heat structures (HTADV) modules.

3.2.2 Reflood relevant routines

From the analysis of Table 3-1, the following list of relevant phenomena where identified:

- interfacial heat transfer;
- wall heat transfer;
- interfacial friction.

The RELAP5-3D code models, closure laws and correlations that are involved in a reflood transient phase are:

- dispersed flow interphase heat transfer model for wet and dry walls;
- wall-to-fluid heat transfer model for transition and film boiling;
- junction interfacial drag coefficient.

The source code of the RELAP5-3D was modified to perturb the main parameters of the models simulating the above phenomena. The list of relevant subroutines was identified from RELAP5-3D manual volume I, [38], and IV [39], and literature [40]. It should be noted that the manual documents are only available to RELAP5-3D license holders.

Table 3-2 is list of modified routines and modules to simulate reflood phase. Names of routines/modules are not shown.

Table 3-2. RELAP5-3D routines for the selected reflood phenomena.

Phenomena	Modified Routine/Module
Interfacial heat transfer	Subroutine to compute interphase heat transfer
Wall heat transfer	Subroutine to compute heat transfer coefficients for the non-reflood side boundary of the reflood model
	Subroutine to compute reflood heat transfer coefficient using the pattern obtained in above subroutine
	Subroutine to compute post-DNB forced convection heat transfer coefficient
Interfacial friction	Subroutine to compute interphase drag
	Subroutine to compute junction interphase drag term for bubbles and droplets
	Subroutine to compute interphase friction coefficients in bubbly/slug flow

Table 3-3 is the list of routine/module for data management (new variables declaration, array modifications). Names of routines/modules are not shown.

Table 3-3. RELAP5-3D modules modified for the BEPU reflood phenomena.

Function	Modified Routine/Module
Calculation support	Subroutine of auxiliary scratch arrays for use in supporting various calculations and functions throughout the program.
Transient control	Subroutine for transient control module.
Heat structure quantity	Subroutine to holds heat structure quantities.
Heat transfer coefficient control	Subroutine to handle entire variables common to the heat transfer coefficient calculations.
Hydrodynamic junction control	Subroutine for hydrodynamic junction data (momentum cells).
Hydrodynamic volume control	Subroutine for hydrodynamic volumes data.
Hydrodynamic data control	Subroutine to control hydrodynamic systems, reference volume, its position coordinates, fluid type in the system, system name, system information flags, system thermodynamic property file name.

Table 3-4 is the list of modified input processing files for user input deck. Names of routines/modules are not shown.

Table 3-4. RELAP5-3D routines modified for BEPU input processing.

Function	**Modified Routine/Module**
Heat transfer boundary condition control	Subroutine to returns left and right boundary conditions for a heat structure.
Component input control	Subroutine for control crosschecking of component input and first pass of component initialization.
Loop control	Subroutine for prepares multiple loop tables, loading number of volumes, junctions and component per loop and establishing the order for processing.
Heat structure data control	Subroutine for routine reading the heat structure component, modified for introducing the additional transition and film boiling coefficients.
Hydrodynamic optional card control	Subroutine for routine reading the optional hydrodynamic system cards that specifies reference volume, its position coordinates, fluid type in the system, the system name, system information flags and the system thermodynamic property file name. Modified for introducing new cards for global perturbation of interfacial friction and heat transfer coefficients.
Pipe component data control	Subroutine to process pipe component data. Modified creating a new card for perturbation of wet and dry wall dispersed flow heat transfer coefficients.
Single junction data control	Subroutine for routine reading the single junction component, modified for testing perturbation of friction coefficient.

3.3 Input deck modifications

The analysis and the modification of the routines identified in the previous paragraph, has led to the modification of the RELAP5-3D input deck. These modifications have the scope of allowing the user to perform perturbation of the selected reflood routines, thus allowing the forward propagation of the models' uncertainties through the code.

Table 3-5. RELAP5-3D new input deck options for BEPU reflood analysis.

Card	**Added words**	**Function**
119	W3(R), W4(R)	added cards W3: system interfacial friction coefficient. Default is 1.0. W4: system interfacial heat transfer coefficient. Default is 1.0.
1CCCG800 or 1CCCG900	W1(I)	added option "6": introduce twenty-four words format for cards 1CCCG801 through 1CCCG899 (left boundary) or 1CCCG901 through 1CCCG999 (right boundary).
1CCCG801 through 1CCCG899 (left boundary) or 1CCCG901 through 1CCCG999 (right boundary).	W1 to W19 are the same as the one for the option "4" (20 words format card) on card 1CCCG800 or 1CCCG900 W20(R) Multiplier on transition boiling heat transfer coefficient – to liquid. The default value is 1.0. W21(R) Multiplier on transition boiling heat transfer coefficient – to gas. The default value is 1.0. W22(R) Multiplier on film boiling heat transfer coefficient – to liquid. The default value is 1.0. W23(R) Multiplier on film boiling heat transfer coefficient – to gas. The default value is 1.0. W24(I) Heat structure number.	Multipliers for "to liquid" and "to gas" heat transfer coefficients for transition and film boiling
CCC0004	W1(R): multiplier for interfacial heat transfer to the liquid - wet wall dispersed flow. The default value is 1.0.	Added new card for perturbing the interfacial heat coefficients for dry and wet wall conditions for pipe components.

	W2(R): multiplier for interfacial heat transfer to the vapor - wet wall dispersed flow. The default value is 1.0. W3(R): multiplier for interfacial heat transfer at the noncondensable gas-liquid interface - wet wall dispersed flow. The default value is 1.0. W4(R): multiplier for interfacial heat transfer to the liquid - dry wall dispersed flow. The default value is 1.0. W5(R): multiplier for interfacial heat transfer to the vapor - dry wall dispersed flow. The default value is 1.0. W6(R): multiplier for interfacial heat transfer at the noncondensable gas-liquid interface - dry wall dispersed flow. The default value is 1.0.	
CCC0110	W5(R): multiplier for the junction interphase friction. The default value is 1.0.	Added word for perturbing interfacial friction coefficient in a single junction component. For testing purposes.

4. RESULTS

Physical models' uncertainties are generally quantified using Separate Effect Tests (SET), Combined Effects Tests (CET) and Integral Tests Facilities (ITF) data. Also, expert elicitation, theoretical limitation analysis and published data on uncertainties can contribute to the physical models' uncertainties determination. The preferred path is to start with a comparison of the physical models results with experiments results. This section shows the comparison between the RELAP5-3D calculations and the FLECHT-SEASET reflood experiment result. The uncertainties bands were clearly observed by using newly added BEPU control module in RELAP5-3D. No tentative to quantify the true input uncertainties distributions has been performed.

4.1 FLECHT-SEASET reflood experiments

As stated above, quantification of the physical models' uncertainties requires the fundamental contribution of experimental data. For demonstrating the capabilities of the new BEPU features implemented in RELAP5-3D, we decided to use as a testbed the Full-Length Emergency Core Heat Transfer Separate Effects and System Effects Tests (FLECHT-SEASET) reflood facility results. Results from this facility already constitute part of the RELAP5-3D code assessment [39], which is only available to RELAP5-3D license holder. No code input deck qualification was necessary.

The FLECHT-SEASET program was an unblocked bundle with forced and gravity reflood being studied. The tests were based on reflood and steam cooling experiments using electrical heater rods to simulate Westinghouse 17 x 17 PWR fuel assembles [40]. Test 31701, a low flooding rate test was run. The bundle cross section is shown in Figure 3-4.

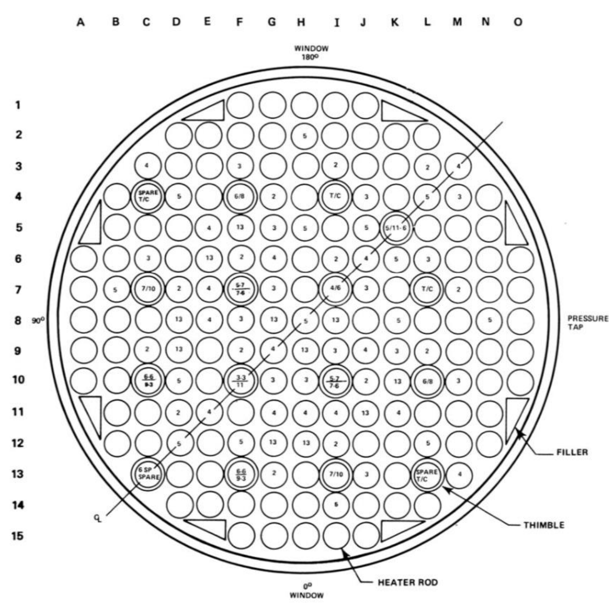

Figure 4-1. FLECHT-SEASET bundle cross section.

The facility design features for forced reflood experiment included:

- a cylindrical low mass bundle housing to minimize housing heat releases;
- housing differential pressure cells every 0.30 to obtain void fraction measurements along the heated length of the bundle;
- steam probes in each of 11 thimbles tubes to measure steam superheat radially and axially across the bundle;
- 177 heater rod thermocouple computer channels;
- housing windows at the 0.91, 1.83 and 2.74 m elevations.

The bundle has the dimensions of a typical PWR (12 feet tall, or 3.658 m) with the exception of the overall radial dimensions. The power to flow area ration is nearly the same as that for a PWR fuel assembly.

The test boundary and initial conditions were the following one:

- initial clad temperature (1.83 elevation): 872 °C
- peak power: 2.3 kW/m
- UP pressure: 0.28 MPa
- injection rate, with LP full: 155.0 mm/s
- flooding water temperature entering LP: 53 °C
- radial power distribution: uniform
- axial power shape: cosine with 1.66 as F_z

The heater rods were simulating the ANS power decay curve plus 20 percent, 30 seconds after the initiation of a LOCA.

4.2 RELAP5-3D / RAVEN UQ

4.2.1 RELAP5-3D FLECHT-SEASET input deck

The RELAP5-3D nodalization of FLECHT-SEASET is based on a pipe (component 6) composed by 20 cells (see Figure 4-2). The measured fluid conditions for the upper lower zones were defined using time dependent volumes (component 5 and 7). The measured flow injection velocity has been used to define the time-dependent junction (component 301) at the bottom the pipe 6. This time dependent junction is modeling the connection between the lower plenum and the assembly. Decay heat was implemented inside the heat structure 61, which models the rod heaters.

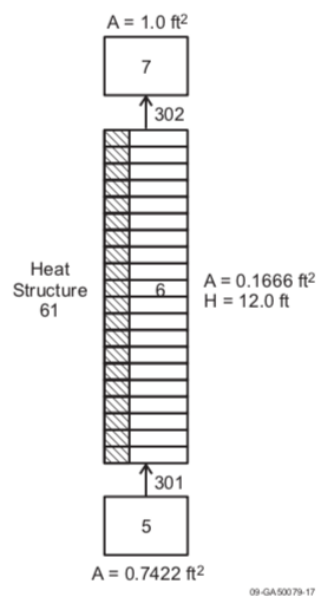

Figure 4-2. RELAP5-3D nodalization for the FLECHT-SEASET forced reflood experiment [39].

4.2.2 RAVEN input deck

In order to perform input uncertainties propagation for the selected physical models (interfacial friction coefficient, interfacial heat transfer, post-DNB heat transfers), the RAVEN code was used [41].

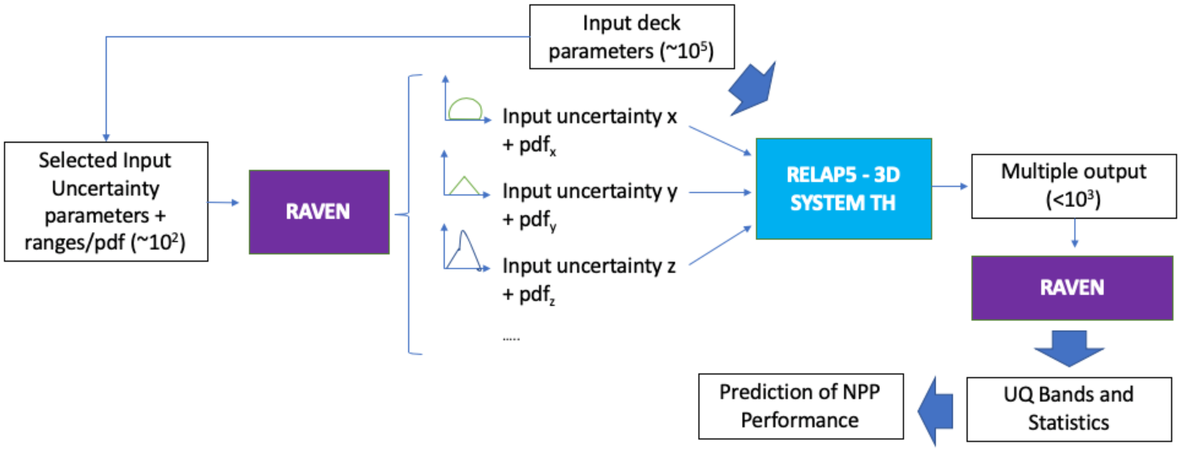

Figure 4-3. RELAP5-3D – RAVEN Coupled Codes for UQ [39].

RAVEN code is a generic software framework to perform parametric and probabilistic analysis based on the response of complex system codes. RAVEN is coupled to RELAP5-3D via an Application Programming Interface (API), which allows the analyst to perform input space sampling using Monte Carlo, Grid or Latin Hyper Cube sampling schemes. RAVEN has the capability to runon High-Performance Computing (HPC) machines, which allows the execution of hundreds of parallel serial runs.

4.2.3 Codes Run

The following input uncertainty distribution was considered (see Table 4-1). The minimum and maximum values for the multipliers are tentative and they are derived from a review of the published literature [42]. Normal distribution was assumed for all the multipliers of the input parameters.

Table 4-1. Testing the Uncertainty Parameters.

Parameter	Distribution	Multiplier MIN	Multiplier MAX
Interfacial junction coefficient	Uniform	0.7	3.5
Dry wall dispersed flow heat transfer coefficient of:			
Liquid	Uniform	0.5	1.2
Vapor	Uniform	0.5	1.2
Noncondensable	Uniform	0.5	1.2
Wet wall dispersed flow heat transfer coefficient of:			

Liquid	Uniform	0.5	1.2
Vapor	Uniform	0.5	1.2
Noncondensable	Uniform	0.5	1.2
Global interfacial heat transfer coefficient	Uniform	0.5	1.2
Transition boiling heat transfer of:			
Liquid	Uniform	0.7	1.3
Vapor	Uniform	0.7	1.3
Film boiling heat transfer of:			
Liquid	Uniform	0.7	1.3
Vapor	Uniform	0.7	1.3

Order-statistics was applied to the sampling, running 153 cases (*m*=4) for a 95/95 distribution (see Section 2.2.2). Results of the calculations of the obtained uncertainty bands for the clad temperature at different elevations and for steam temperatures are reported in the following figures.

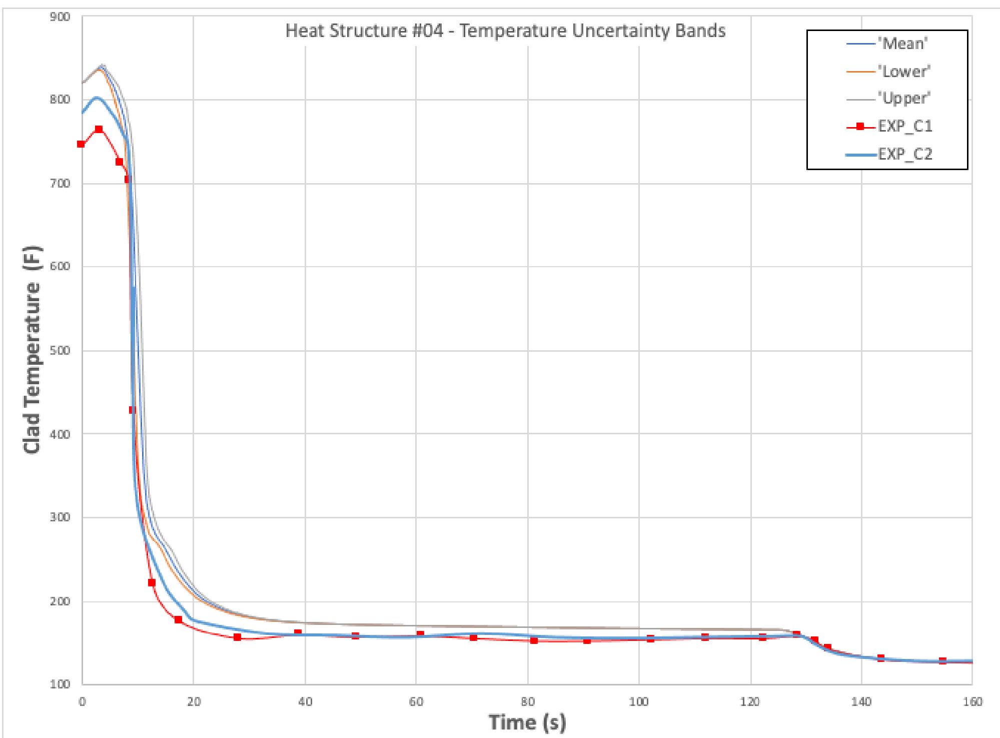

Figure 4-4. FLECHT-SEASET Clad Temperature at elevation 0.62 m.

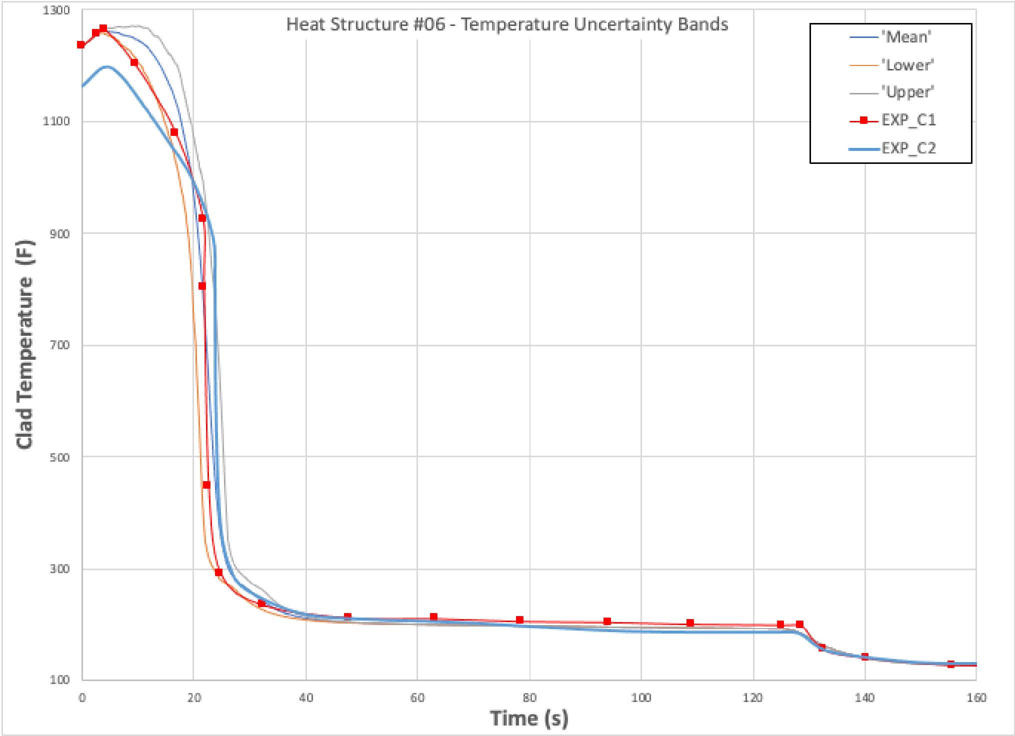

Figure 4-5. FLECHT-SEASET Clad Temperature at elevation 0.99 m.

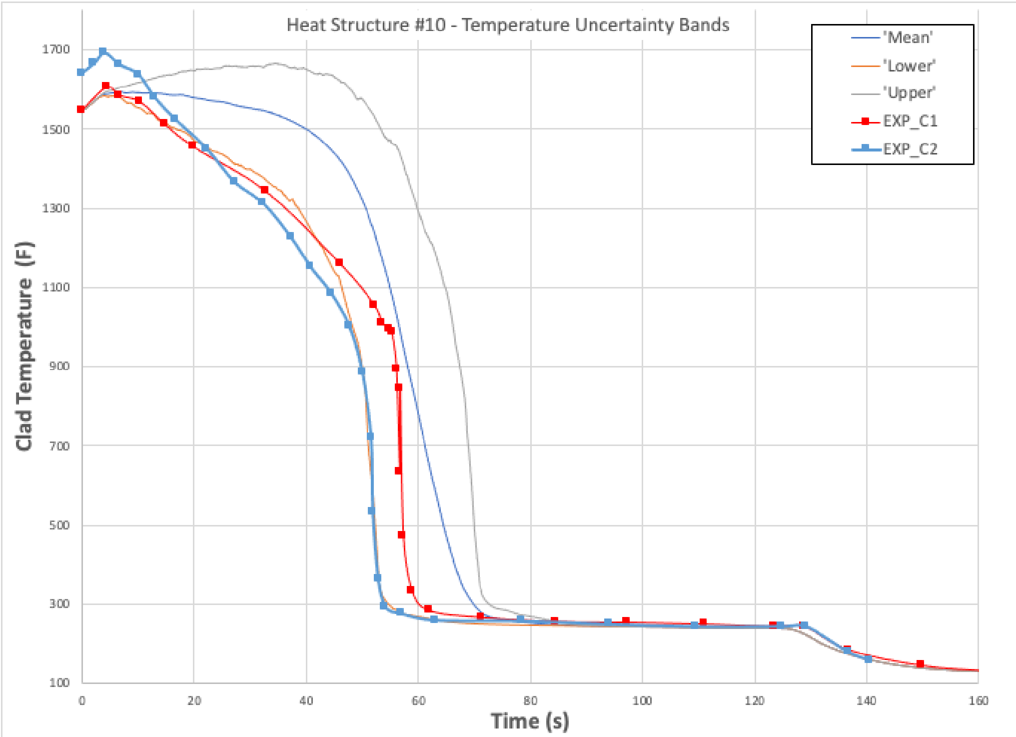

Figure 4-6. FLECHT-SEASET Clad Temperature at elevation 1.78 m.

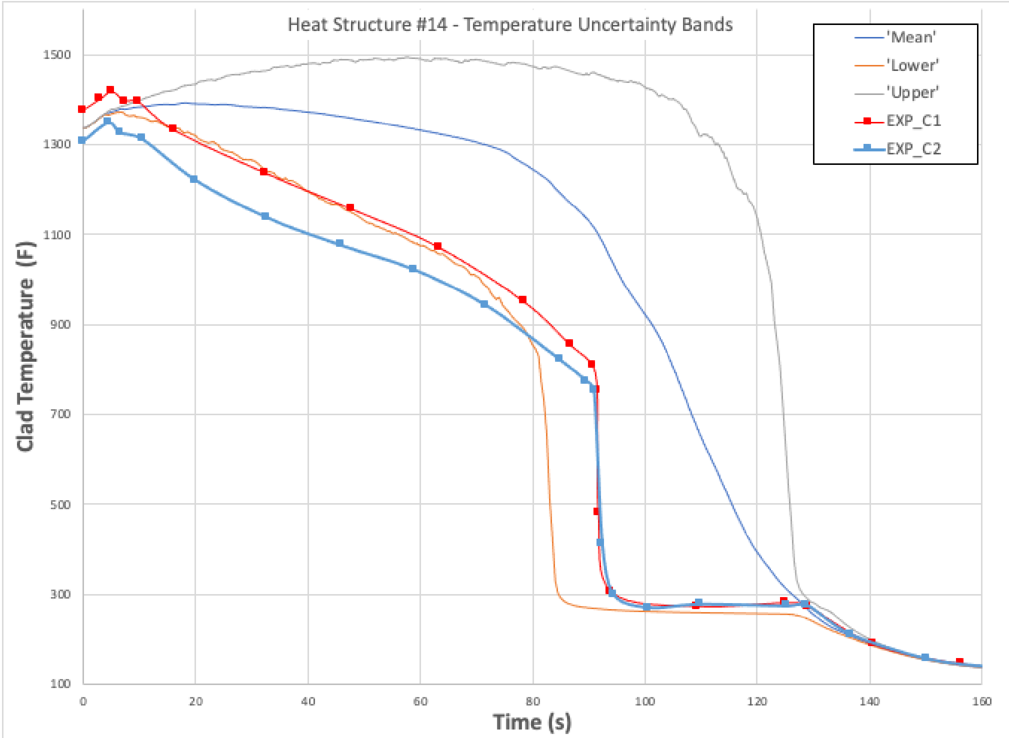

Figure 4-7. FLECHT-SEASET Clad Temperature at elevation 2.46 m.

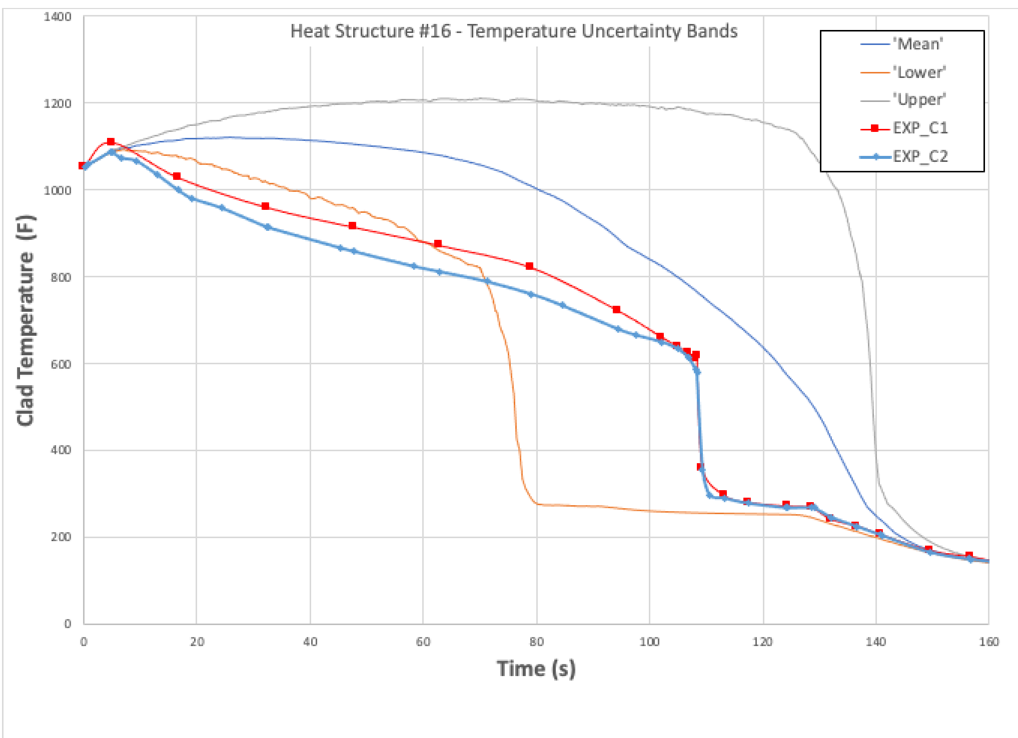

Figure 4-8. FLECHT-SEASET Clad Temperature at elevation 2.834 m.

5. CONCLUSIONS AND FUTURE WORKS

This report documents the FY 2020 activities for introducing BEPU capabilities in the INL system-thermal-hydraulic code RELAP5-3D. As we have shown in the second chapter of the report, BEPU is today the state-of-the-art calculation framework for analyzing the safety performance of the LWR systems. The large investments that have been dedicated during the past years in developing UQ methodologies and BE codes have resulted in increased safety margins and economic performance of the LWR fleet. However, a further step toward realistic analysis would require the introduction of a Risk-Informed approach, which implies the use of a BEPU-ready system thermal-hydraulic code. Therefore, the development of the models' uncertainties propagation capabilities for RELAP5-3D code is a necessary step toward the implementation of the RISA pathway and toward providing an effective support to the different RISA-pathway pilot-projects.

The first step we took in this FY 2020 was to develop RELAP5-3D capabilities for perturbing relevant parameters of models invoked by the code during the reflood phase of a LB-LOCA simulation. Those capabilities have been implemented through:

- a review of the RELAP5-3D source code, with the identification of the proper routines and correlations;
- the introduction of dedicated multipliers for perturbing the models' main parameters;
- the modification of the code input structure, for allowing the direct uncertainty propagation by a safety analyst without having the need of accessing the source code.

The testing of the code modifications on the FLECHT-SEASET experiments, using the RAVEN/RELAP5-3D coupled codes, has demonstrated the possibility of obtaining uncertainty bands and of assessing the importance of the different models influencing the FOM by performing statistical analysis.

The future works will be devoted to:

- the exposure of the relevant closure laws for the other LOCA phases (blowdown, refill) and for other FSAR DBAs (e.g. MSLB, RIA);
- the source code modification and the testing with SET/CET/ITF data;
- the integration of the RELAP5-3D/BEPU with RAVEN, EMRALD and HUNTER codes, for the delivery to the LWR community of a full Risk-Informed safety analysis software package.

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7. APPENDIX A – RAVEN UQ INPUT DECK

<u>Uncertainty Propagation</u>

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    <Sequence>Ptest_DummyStep</Sequence>
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    mpi
    <runQSUB/>
    </mode>
    <NumMPI>1</NumMPI>
    <clusterParameters>-P lwrs</clusterParameters>
    <expectedTime>00:15:00</expectedTime>
  </RunInfo>

  <Files>
    <Input name="flecht31701_A3.i" type="">flecht31701_A3.i</Input>
    <Input name="tpfh2o"           type="">tpfh2o</Input>
  </Files>

<Models>
    <Code name="MyRELAP" subType="Relap5">
      <executable>~/projects/raven/relap_BEPU/relap5.x</executable>
    </Code>
 </Models>

<Distributions>
    <Uniform name="PSTDNB">
      <upperBound>1.3</upperBound>
      <lowerBound>0.7</lowerBound>
    </Uniform>
    <Uniform name="FRICT_GLOBAL">
      <upperBound>3.5</upperBound>
      <lowerBound>0.7</lowerBound>
    </Uniform>
    <Uniform name="DISP">
      <upperBound>1.2</upperBound>
      <lowerBound>0.5</lowerBound>
    </Uniform>
</Distributions>

  <Samplers>
    <Stratified name="LHS">
      <variable name="1|0000119:3">
          <distribution>FRICT_GLOBAL</distribution>
          <grid type='CDF' construction='equal' steps='153' >0.0 1.0</grid>
      </variable>
      <variable name="1|0060004:1,1|0060004:2,1|0060004:3">
          <distribution>DISP</distribution>
          <grid type='CDF' construction='equal' steps='153' >0.0 1.0</grid>
      </variable>
      <variable name="1|0060004:4,1|0060004:5,1|0060004:6">
          <distribution>DISP</distribution>
          <grid type='CDF' construction='equal' steps='153' >0.0 1.0</grid>
      </variable>
      <variable
name="1|10061901:20,1|10061901:21,1|10061902:20,1|10061902:21,1|10061903:20,1|10061903:21,1|10061904:20
,1|10061904:21,1|10061905:20,1|10061905:21,1|10061906:20,1|10061906:21,1|10061907:20,1|10061907:21,1|10
061908:20,1|10061908:21,1|10061909:20,1|10061909:21,1|10061910:20,1|10061910:21,1|10061911:20,1|1006191
1:21,1|10061912:20,1|10061912:21,1|10061913:20,1|10061913:21,1|10061914:20,1|10061914:21,1|10061915:20,
```

```
1|10061915:21,1|10061916:20,1|10061916:21,1|10061917:20,1|10061917:21,1|10061918:20,1|10061918:21,1|100
61919:20,1|10061919:21,1|10061920:20,1|10061920:21">
              &lt;distribution&gt;PSTDNB&lt;/distribution&gt;
              &lt;grid type='CDF' construction='equal' steps='153' &gt;0.0 1.0&lt;/grid&gt;
          &lt;/variable&gt;
        &lt;/Stratified&gt;
      &lt;/Samplers&gt;

      &lt;Steps&gt;
        &lt;MultiRun name="Ptest_DummyStep" verbosity="debug"  re-seeding="1"&gt;
          &lt;Input class="Files" type=""&gt;flecht31701_A3.i&lt;/Input&gt;
          &lt;Input class="Files" type=""&gt;tpfh2o&lt;/Input&gt;
          &lt;Model class="Models" type="Code"&gt;MyRELAP&lt;/Model&gt;
          &lt;Sampler class="Samplers" type="Stratified"&gt;LHS&lt;/Sampler&gt;
          &lt;Output  class="Databases" type="HDF5"&gt;DataB_REL5_1&lt;/Output&gt;
        &lt;/MultiRun&gt;
      &lt;/Steps&gt;

      &lt;Databases&gt;
        &lt;HDF5 name="DataB_REL5_1" readMode="overwrite"/&gt;
      &lt;/Databases&gt;

    &lt;/Simulation&gt;
```

Post-processing example

```
<?xml version="1.0" ?>
<Simulation verbosity="all">
  <RunInfo>
    <WorkingDir>.</WorkingDir>
    <Sequence>LOAD, SYNCRONIZE, STATICS</Sequence>
    <batchSize>1</batchSize>
  </RunInfo>

  <Models>
    <PostProcessor name="syncronizeHistorySet" subType="InterfacedPostProcessor">
      <method>HistorySetSync</method>
      <pivotParameter>time</pivotParameter>
      <extension>zeroed</extension>
      <syncMethod>grid</syncMethod>
      <numberOfSamples>10000</numberOfSamples>
    </PostProcessor>
    <PostProcessor name="alpha" subType="BasicStatistics">
      <expectedValue prefix="mean">httemp_61014_7</expectedValue>
      <percentile prefix="percentile">httemp_61014_7</percentile>
      <sigma prefix="sigma">httemp_61014_7</sigma>
      <maximum prefix="max">httemp_61014_7</maximum>
      <minimum prefix="min">httemp_61014_7</minimum>
      <pivotParameter>time</pivotParameter>
    </PostProcessor>

  </Models>

  <Files>
    <Input name="OutStatics2" type="csv">OutStatics2.csv</Input>
  </Files>

  <Steps>
    <IOStep name="LOAD">
      <Input class="Databases" type="HDF5">DataB_REL5_1</Input>
      <Output class="DataObjects" type="HistorySet">DATA_OUT</Output>
    </IOStep>
    <PostProcess name="SYNCRONIZE">
      <Input class="DataObjects" type="HistorySet">DATA_OUT</Input>
      <Model class="Models" type="PostProcessor">syncronizeHistorySet</Model>
      <Output class="DataObjects" type="HistorySet">HistorySetPostProcTestSyncronized</Output>
    </PostProcess>
    <PostProcess name="STATICS">
      <Input class="DataObjects" type="HistorySet">HistorySetPostProcTestSyncronized</Input>
      <Model class="Models" type="PostProcessor">alpha</Model>
      <Output class="DataObjects" type="HistorySet">alpha_basicStatPP</Output>
      <Output class="OutStreams" type="Print">alpha_basicStatPP_dump</Output>
    </PostProcess>
  </Steps>

  <Databases>
    <HDF5 name="DataB_REL5_1" readMode="read"/>
  </Databases>

  <DataObjects>
    <HistorySet name="DATA_OUT">
<Input>1|0000119:3,1|0060004:1,1|0060004:2,1|0060004:3,1|0060004:4,1|0060004:5,1|0060004:6,1|10061901:2
0,1|10061901:21,1|10061902:20,1|10061902:21,1|10061903:20,1|10061903:21,1|10061904:20,1|10061904:21,1|1
0061905:20,1|10061905:21,1|10061906:20,1|10061906:21,1|10061907:20,1|10061907:21,1|10061908:20,1|100619
08:21,1|10061909:20,1|10061909:21,1|10061910:20,1|10061910:21,1|10061911:20,1|10061911:21,1|10061912:20
,1|10061912:21,1|10061913:20,1|10061913:21,1|10061914:20,1|10061914:21,1|10061915:20,1|10061915:21,1|10
061916:20,1|10061916:21,1|10061917:20,1|10061917:21,1|10061918:20,1|10061918:21,1|10061919:20,1|1006191
9:21,1|10061920:20,1|10061920:21</Input>
      <Output>time, httemp_61014_7</Output>
    </HistorySet>
    <HistorySet name="HistorySetPostProcTestSyncronized">
<Input>1|0000119:3,1|0060004:1,1|0060004:2,1|0060004:3,1|0060004:4,1|0060004:5,1|0060004:6,1|10061901:2
0,1|10061901:21,1|10061902:20,1|10061902:21,1|10061903:20,1|10061903:21,1|10061904:20,1|10061904:21,1|1
```

```
0061905:20,1|10061905:21,1|10061906:20,1|10061906:21,1|10061907:20,1|10061907:21,1|10061908:20,1|100619
08:21,1|10061909:20,1|10061909:21,1|10061910:20,1|10061910:21,1|10061911:20,1|10061911:21,1|10061912:20
,1|10061912:21,1|10061913:20,1|10061913:21,1|10061914:20,1|10061914:21,1|10061915:20,1|10061915:21,1|10
061916:20,1|10061916:21,1|10061917:20,1|10061917:21,1|10061918:20,1|10061918:21,1|10061919:20,1|1006191
9:21,1|10061920:20,1|10061920:21</Input>
          <Output>time, httemp_61014_7</Output>
        </HistorySet>
        <PointSet name="PRINT">
          <Input>time</Input>
          <Output>expv, 95up, 5down, max, min</Output>
        </PointSet>
        <PointSet name="WILKSMAX">

<Input>1|0000119:3,1|0060004:1,1|0060004:2,1|0060004:3,1|0060004:4,1|0060004:5,1|0060004:6,1|10061901:2
0,1|10061901:21,1|10061902:20,1|10061902:21,1|10061903:20,1|10061903:21,1|10061904:20,1|10061904:21,1|1
0061905:20,1|10061905:21,1|10061906:20,1|10061906:21,1|10061907:20,1|10061907:21,1|10061908:20,1|100619
08:21,1|10061909:20,1|10061909:21,1|10061910:20,1|10061910:21,1|10061911:20,1|10061911:21,1|10061912:20
,1|10061912:21,1|10061913:20,1|10061913:21,1|10061914:20,1|10061914:21,1|10061915:20,1|10061915:21,1|10
061916:20,1|10061916:21,1|10061917:20,1|10061917:21,1|10061918:20,1|10061918:21,1|10061919:20,1|1006191
9:21,1|10061920:20,1|10061920:21</Input>
          <Output>time, httemp_61014_7</Output>
        </PointSet>
        <HistorySet name="alpha_basicStatPP">
          <options>
            <pivotParameter>time</pivotParameter>
          </options>
          <Output>alpha_vars</Output>
        </HistorySet>
      </DataObjects>

      <OutStreams>
        <Print name="chart">
          <source>PRINT</source>
          <type>csv</type>
        </Print>
        <Print name="chart2">
          <source>WILKSMAX</source>
          <type>csv</type>
        </Print>
        <Print name="alpha_basicStatPP_dump">
          <type>csv</type>
          <source>alpha_basicStatPP</source>
        </Print>
      </OutStreams>

      <VariableGroups>
        <Group name="alpha_vars">mean_httemp_61014_7,
                     percentile_5_httemp_61014_7,
                     percentile_95_httemp_61014_7,
                     sigma_httemp_61014_7,
                     max_httemp_61014_7,
                     min_httemp_61014_7</Group>
      </VariableGroups>

    </Simulation>
```

8. APPENDIX B – RELAP5-3D FLECHT-SEASET INPUT DECK – TEST 31701

```
=flecht-seaset developmental assessment case - test 31701
*deck flecht31701.i
*
* RELAP5-3D Developmental Assessment modifications by Paul Bayless, November 2008
*
*
* Modified by C. Parisi for DOE-LWRS/RISA/MP-BEPU Project, new Cards introduced in
* the input deck for Uncertainty propagation for interfacial heat transfer, interfacial
* friction coefficient, transition and film boiling. August 2020.
*
* This deck was modified from that used in previous assessments (fs31701.i).
* The bundle hydraulic diameter was changed to 0.03191. This value was taken from
* Ken Carlson's MOD3.2 assessment deck for test 35557, which has the same rod
* bundle. The junction hydraulic diameter is specified to be the same value. The
* heat structure heated diameter is unchanged. The bundle volume flag was set to 1.
* Added reflood quantities to plot file and collapsed liquid level control variable.
* Semi-implicit solution scheme used.
*
0000100 new transnt
0000101 run
0000102 british  british
0000105      5.     6.
0000119 -1.0  fixed 1.0
0000201  80.0  1.0e-07   0.020        3     25    100    1000
0000202 120.0  1.0e-07   0.025        3     20    400    1600
0000203 160.0  1.0e-07   0.050        3     10    400    1600
0000301 httemp      6100407
0000302 httemp      6100607
0000303 httemp      6100707
0000304 httemp      6101007
0000305 httemp      6101407
0000306 httemp      6101607
0000307 httemp      6101707
0000308 voidg       006020000
0000309 voidg       006060000
0000310 voidg       006110000
0000311 voidg       006160000
0000312 voidg       006190000
20800001 zqbot      0061
20800002 zqtop      0061
*
***************************************************************
*                                                             *
*                     volume data cards                       *
*                                                             *
***************************************************************
*
*
* lower plenum (vol no. 1)
*
0050000   "low-pl"  tmdpvol
0050101   0.7422     1.57       0.0     0.0    90.0    1.57     0. 0. 0
0050200   3
0050201    200.00   40.0000  127.0
*
* junction no. 2  (lower plenum to core)
*
3010000   "jun  2"  tmdpjun
3010101   005000000  006000000  0.0
3010200   0
3010201        .500    .219    .219   0.000       5.000    .528    .528 0.
3010202      10.000    .522    .522   0.000      15.000    .520    .520 0.
3010203      20.000    .518    .518   0.000      25.000    .516    .516 0.
3010204      30.000    .515    .515   0.000      35.000    .515    .515 0.
3010205      40.000    .514    .514   0.000      45.000    .513    .513 0.
3010206      50.000    .514    .514   0.000      55.000    .514    .514 0.
```

```
3010207      60.000    .513    .513   0.000      65.000    .512    .512 0.
3010208      70.000    .512    .512   0.000      75.000    .512    .512 0.
3010209      80.000    .512    .512   0.000      85.000    .513    .513 0.
3010210      90.000    .512    .512   0.000      95.000    .514    .514 0.
3010211     100.000    .511    .511   0.000     105.000    .512    .512 0.
3010212     110.000    .511    .511   0.000     115.000    .511    .511 0.
3010213     120.000    .510    .510   0.000     125.000    .512    .512 0.
3010214     130.000    .511    .511   0.000     135.000    .512    .512 0.
3010215     140.000    .512    .512   0.000     145.000    .511    .511 0.
3010216     150.000    .512    .512   0.000     155.000    .513    .513 0.
3010217     160.000    .512    .512   0.000     165.500    .512    .512 0.
3010218     170.500    .511    .511   0.000     175.500    .511    .511 0.
3010219     180.500    .511    .511   0.000     185.500    .512    .512 0.
3010220     190.500    .512    .512   0.000     195.500   -.001   -.001 0.
3010221     201.000   -.001   -.001   0.000
*
* core (vol no. 2)
*
0060000   "core" pipe
0060001   20
0060004   1.0 1.0 1.0
+ 1.0 1.0 1.0
0060101   0.1666     20
0060301   0.6000     20
0060401   0.09996    20
0060601   90.0       20
*0060801   0.0        0.0386     20
0060801   0.0        0.03191    20
*0061001   00         20
0061001   100        20
0061101   0000       19
0061201   3          40.0112    478.00   0.0    0.0  0  1
0061202   3          40.0108    582.00   0.0    0.0  0  2
0061203   3          40.0104    686.15   0.0    0.0  0  3
0061204   3          40.0100    820.45   0.0    0.0  0  4
0061205   3          40.0096    1035.28  0.0    0.0  0  5
0061206   3          40.0092    1236.62  0.0    0.0  0  6
0061207   3          40.0088    1289.62  0.0    0.0  0  7
0061208   3          40.0084    1371.75  0.0    0.0  0  8
0061209   3          40.0080    1459.71  0.0    0.0  0  9
0061210   3          40.0076    1547.65  0.0    0.0  0  10
0061211   3          40.0072    1559.22  0.0    0.0  0  11
0061212   3          40.0068    1519.12  0.0    0.0  0  12
0061213   3          40.0064    1484.80  0.0    0.0  0  13
0061214   3          40.0060    1336.75  0.0    0.0  0  14
0061215   3          40.0056    1198.46  0.0    0.0  0  15
0061216   3          40.0052    1056.09  0.0    0.0  0  16
0061217   3          40.0048    868.73   0.0    0.0  0  17
0061218   3          40.0044    747.65   0.0    0.0  0  18
0061219   3          40.0040    653.78   0.0    0.0  0  19
0061220   3          40.0036    559.91   0.0    0.0  0  20
0061300   0
0061301   0.0        0.0        0.0     19
0061401   0.03191  1.  1.  1.  19
*
* upper plenum
*
0070000 "up-plen" tmdpvol
0070101   1.   1.   0.   0.   90.   1.   0.   0.   0
0070200   3
0070201     200.0   40.0     400.0
*
3020000  coretoup  sngljun
3020101   006010000  007000000  0.0     0.0    0.0     0100
3020110   0.         0.         1.      1.     1.3
3020201   1          0.0        0.0     0.0
*
**************************************************************
*                                                            *
*              heat slab structure                           *
*                                                            *
**************************************************************
*
```

```
*  core heater rods
*
10061000    20   7   2   0   0.   1    1   16
*
10061100    0           2
10061101    0.00396     1
10061102    0.00333     2
10061103    0.003105    4
10061104    0.00104     6
10061201    2           1
*
10061202    1           2
10061203    2           4
10061204    3           6
*
10061301    0.0         1
10061302    1.0         2
10061303    0.0         6
*
10061400    -1
10061401    478.00  478.00  478.00  478.00  478.00  478.00  478.00
10061402    582.00  582.00  582.00  582.00  582.00  582.00  582.00
10061403    686.15  686.15  686.15  686.15  686.15  686.15  686.15
10061404    820.45  820.45  820.45  820.45  820.45  820.45  820.45
10061405    1035.28 1035.28  1035.28  1035.28  1035.28  1035.28  1035.28
10061406    1236.62 1236.62  1236.62  1236.62  1236.62  1236.62  1236.62
10061407    1289.62 1289.62  1289.62  1289.62  1289.62  1289.62  1289.62
10061408    1371.75 1371.75  1371.75  1371.75  1371.75  1371.75  1371.75
10061409    1459.71 1459.71  1459.71  1459.71  1459.71  1459.71  1459.71
10061410    1547.65 1547.65  1547.65  1547.65  1547.65  1547.65  1547.65
10061411    1559.22 1559.22  1559.22  1559.22  1559.22  1559.22  1559.22
10061412    1519.12 1519.12  1519.12  1519.12  1519.12  1519.12  1519.12
10061413    1484.80 1484.80  1484.80  1484.80  1484.80  1484.80  1484.80
10061414    1336.75 1336.75  1336.75  1336.75  1336.75  1336.75  1336.75
10061415    1198.46 1198.46  1198.46  1198.46  1198.46  1198.46  1198.46
10061416    1056.09 1056.09  1056.09  1056.09  1056.09  1056.09  1056.09
10061417    868.73  868.73  868.73  868.73  868.73  868.73  868.73
10061418    747.65  747.65  747.65  747.65  747.65  747.65  747.65
10061419    653.78  653.78  653.78  653.78  653.78  653.78  653.78
10061420    559.91  559.91  559.91  559.91  559.91  559.91  559.91
*
10061501    0           0         0   0     0.0      20
*
10061601    006010000   10000     1   0     9.4584   20
*
10061701    100         0.0215    0   0    1
10061702    100         0.0215    0   0    2
10061703    100         0.0215    0   0    3
10061704    100         0.0340    0   0    4
10061705    100         0.0440    0   0    5
10061706    100         0.0555    0   0    6
10061707    100         0.0650    0   0    7
10061708    100         0.0745    0   0    8
10061709    100         0.0800    0   0    9
10061710    100         0.0830    0   0    10
10061711    100         0.0830    0   0    11
10061712    100         0.0800    0   0    12
10061713    100         0.0745    0   0    13
10061714    100         0.0650    0   0    14
10061715    100         0.0555    0   0    15
10061716    100         0.0440    0   0    16
10061717    100         0.0340    0   0    17
10061718    100         0.0215    0   0    18
10061719    100         0.0215    0   0    19
10061720    100         0.0215    0   0    20
*
*left
10061801   .1      .3   .3    0.     0.     0.     0.     1.  20
*      only the hydraulic diameter matters since chfcal is not
*           called when reflood is on.
*right
10061900   6
*                            elev  elev    k       k
```

```
*flags   htdiam elev el-rev grid-f grid-r gridk-f gridk-r apf  num
10061901  .03844  .3  11.7   .3     1.4      .1     .1     .43
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+  1.0    1.0     1
10061902  .03844  .9  11.1   .9      .8      .1     .1     .43
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+ 1.0    1.0     2
10061903  .03844 1.5  10.5  1.5      .2      .1     .1     .43
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+  1.0    1.0     3
10061904  .03844 2.1   9.9   .4     1.3      .1     .1     .68
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+  1.0    1.0     4
10061905  .03844 2.7   9.3  1.0      .7      .1     .1     .88
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+  1.0    1.0     5
10061906  .03844 3.3   8.7  1.6      .1      .1     .1    1.11
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+  1.0    1.0     6
10061907  .03844 3.9   8.1   .5     1.2      .1     .1    1.30
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+  1.0    1.0     7
10061908  .03844 4.5   7.5  1.1      .6      .1     .1    1.49
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+  1.0    1.0     8
10061909  .03844 5.1   6.9  1.7     .04      .1     .1    1.60
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+  1.0    1.0     9
10061910  .03844 5.7   6.3   .6     1.1      .1     .1    1.66
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+   1.0    1.0     10
10061911  .03844 6.3   5.7  1.2      .5      .1     .1    1.66
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+  1.0    1.0     11
10061912  .03844 6.9   5.1   .1     1.6      .1     .1    1.60
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+  1.0    1.0     12
10061913  .03844 7.5   4.5   .7     1.0      .1     .1    1.49
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+  1.0    1.0     13
10061914  .03844 8.1   3.9  1.3      .4      .1     .1    1.30
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+   1.0    1.0     14
10061915  .03844 8.7   3.3   .2     1.6      .1     .1    1.11
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+  1.0    1.0     15
10061916  .03844 9.3   2.7   .8     1.0      .1     .1     .88
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+   1.0    1.0     16
10061917  .03844 9.9   2.1  1.4      .4      .1     .1     .68
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+   1.0    1.0     17
10061918  .03844 10.5  1.5   .2     1.5      .1     .1     .43
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+   1.0    1.0     18
```

```
10061919  .03844 11.1   .9   .8      .9      .1     .1     .43
+          .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0     1.0  1.0   1.0   1.0
+  1.0    1.0     19
10061920  .03844 11.7   .3  1.4      .3      .1     .1     .43
+         .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0    1.0  1.0   1.0   1.0
+       1.0    1.0     20
*
*
*****************************************************
*     heat structure thermal property data          *
*****************************************************
*
*
20100100   tbl/fctn    1       1    * kanthac
20100200   tbl/fctn    1       1    * boron nitride
20100300   tbl/fctn    1       1    * stainless steel
*
*
*      thermal conductivity tables
*
* kanthac
*
20100101  0.0         .002694
20100102  1000.0      .003889
20100103  2000.0      .005083
20100104  4000.0      .007472
*
* boron nitride
*
20100201  100.0       .00408
20100202  400.0       .00406
20100203  600.0       .00396
20100204  800.0       .00390
20100205  1000.0      .00386
20100206  1200.0      .00381
20100207  1400.0      .00376
20100208  1600.0      .00371
20100209  1800.0      .00366
20100210  2000.0      .00361
20100220  4000.0      .00312
*
* stainless steel
*
*20100301  0.0         .002
20100302  70.0        .002415
20100303  400.0       .0028
20100304  600.0       .00303
20100305  800.0       .00327
20100306  1000.0      .0035
20100307  1200.0      .00373
20100308  1400.0      .00397
20100309  1600.0      .0042
20100310  1800.0      .00443
20100311  2000.0      .0046667
20100312  4000.0      .007
*
*
*     volumetric heat capacity
*
* kanthac
*
20100151  0.0         48.61
20100152  1200.       80.28
20100153  1400.0      124.88
20100154  1600.0      79.39
20100155  2200.0      82.51
*
* boron nitride
*
20100251   70.0       22.31
20100252  200.0       28.44
```

```
20100253  400.0       36.00
20100254  600.0       41.75
20100255  800.0       46.14
20100256  1000.0      49.47
20100257  1200.0      52.02
20100258  1400.0      53.95
20100259  1600.0      55.43
20100260  1800.0      56.55
20100261  2000.0      57.41
20100262  2400.0      58.56
*
* stainless steel
*
20100351  70.0        54.45
20100352  200.0       56.94
20100353  400.0       60.78
20100354  600.0       64.62
20100355  800.0       66.84
20100356  1000.0      69.06
20100357  1400.0      73.49
20100358  1800.0      77.93
20100359  2200.0      82.37
20100360  2400.0      84.59
*
**********************************
*          power table          *
**********************************
*
20210000  power
20210001     .5000     .8044             5.0000     .7870
20210002   10.0000     .7657            15.0000     .7492
20210003   20.0000     .7348            25.0000     .7222
20210004   30.0000     .7108            35.0000     .7028
20210005   40.0000     .6924            45.0000     .6835
20210006   50.0000     .6750            55.0000     .6685
20210007   60.0000     .6618            65.0000     .6547
20210008   70.0000     .6472            75.0000     .6409
20210009   80.0000     .6347            85.0000     .6284
20210010   90.0000     .6219            95.0000     .6163
20210011  100.0000     .6114           105.0000     .6065
20210012  110.0000     .6018           115.0000     .5965
20210013  120.0000     .5909           125.0000     .5865
20210014  130.0000     .0322           135.0000     .0027
20210015  140.0000     .0018           145.0000     .0017
20210016  150.0000     .0017           155.0000     .0017
20210017  160.0000     .0017           165.5000     .0015
20210018  170.5000     .0015           175.5000     .0017
20210019  180.5000     .0017           185.5000     .0015
20210020  190.5000     .0015           195.5000     .0017
*
**********************************
* control variables
**********************************
* collapsed liquid level
20500600  corelev  sum  1.0  0.0  0
20500601  0.0  0.6 voidf 6010000  0.6 voidf 6020000
20500602       0.6 voidf 6030000  0.6 voidf 6040000
20500603       0.6 voidf 6050000  0.6 voidf 6060000
20500604       0.6 voidf 6070000  0.6 voidf 6080000
20500605       0.6 voidf 6090000  0.6 voidf 6100000
20500606       0.6 voidf 6110000  0.6 voidf 6120000
20500607       0.6 voidf 6130000  0.6 voidf 6140000
20500608       0.6 voidf 6150000  0.6 voidf 6160000
20500609       0.6 voidf 6170000  0.6 voidf 6180000
20500610       0.6 voidf 6190000  0.6 voidf 6200000
*
*  end of problem
*
.
```